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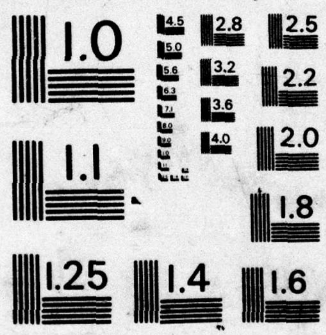

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FINAL SCIENTIFIC REPORT

ON

CONTROL SYSTEMS THEORY

under

Grant 71-2116

See Form 1473

Principal Investigators: Professor J. S. Meditch
Professor A. R. Stubberud

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SCHOOL OF ENGINEERING

University of California, Irvine
Irvine, California

FINAL SCIENTIFIC REPORT

on

CONTROL SYSTEMS THEORY

School of Engineering
University of California
Irvine, California 92717

August 1976

Principal Investigators

Professor J. S. Meditch

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CONTENTS

ABSTRACT

Research conducted under AFOSR Grant 71-2116, Control Systems Theory, during the five-year term of the grant, 1 July 1971 to 30 June 1976, is comprehensively reviewed. The work is classified into the two major categories of estimation theory and control theory. Within the former, results are reported in the areas of polynomial filtering, adaptive filtering, data smoothing, applied estimation theory, observer theory, and data compression and random sampling. In the latter, the focus is on multivariable control system design, and the research presented is in the areas of computer-aided design, design theory, controls-configured systems, and multivariable servomechanisms. A chronological listing of 45 publications and 9 Ph.D. theses that resulted from the research supported by the grant is included.

I. INTRODUCTION

This document is the final scientific report for AFOSR Grant 71-2116, Control Systems Theory. The term of the grant was the five-year period 1 July 1971 to 30 June 1976. The Principal Investigators were Professors J. S. Meditch and A. R. Stubberud of the School of Engineering, University of California, Irvine.

The research conducted under the grant falls into two major categories: Estimation Theory and Control Theory. Within the former, work was carried out in the areas of polynomial filtering, adaptive filtering, data smoothing, applied estimation theory, observer theory, and data compression and random sampling. The results of this work are described in Section II.

In the category of Control Theory, research was pursued in computer-aided design, design theory, controls-configured systems, and multivariable servomechanisms. This work is reported upon in Section III.

A chronological bibliography of all publications, AFOSR scientific reports and significant papers, including those planned for publication, is given in Section IV. It is noted that research under AFOSR Grant 71-2116 has led to 45 such publications.

In addition to the work of the Principal Investigators, the grant supported in part or in full the doctoral research of 9 graduate students. All of this research was supervised and contributed to by the Principal Investigators. A chronological listing of the Ph.D. research so conducted is presented in Section V.

II. ESTIMATION THEORY

The six areas in which research studies were pursued in the category of estimation theory are described below. The name of the

Principal Investigator who was in charge of each area is as indicated.

1. Polynomial Filtering (Professor A. R. Stubberud).

Research in polynomial filtering was conducted in two areas:

a. Synthesis procedures for nonlinear filters in which the nonlinearities are constrained to finite order polynomials

b. Application of polynomial estimators to covariance identification

a. Polynomial filters

A study was performed on the properties of optimal nonlinear filters which generate estimates in the form of finite order polynomials of the elements of the observation sequence. The study shows that practical polynomial filters can be generated which in some cases are preferable to some of the more popular filters such as the "Extended Kalman Filter." Using truncated power series expansions and polynomial estimation theory, a "High Order Extended Kalman Filter" was developed which can improve accuracy over the standard "Extended Kalman Filter." Documention of some of these results appears in [18].

b. Covariance identification

A study was completed on the application of polynomial estimators for the plant and measurement noise covariance elements of a Kalman type of filter. A sequential algorithm was developed and studied on a digital computer and statistical methods were generated to verify the algorithm. The results are documented in [11].

2. Adaptive Filtering (Professor A. R. Stubberud).

Research in adaptive filtering has been conducted in two areas:

a. Adaptation by configuration control

b. Identification based on properties of the residual

a. Adaptation by configuration control

A study was performed in which the confuguration of the system was controlled in such a way as to improve filter performance. The technique

was applied (via simulation) to a missile launcher system and a significant improvement in performance was obtained over the a priori system. This study was completed and the final documentaion of results is given in [24].

b. Identification based on properties of the residual

Studies were performed in which algorithms, based on the innovations properties, were developed for identifying the plant parameters and noise statistics of a linear, time-invariant discrete time system. One of these algorithms has a separation property which allows identification of the plant parameters independent of the noise statistics. Some of the results of these studies are documented in references [28, 29, 35, 36, 40].

3. Data Smoothing (Professor J. S. Meditch)

The area of data smoothing deals with the problem of extracting useful information, e.g., messages and system parameters, from noisy signals in such a way as to maximize the quality of the extracted information. Research in this area was carried out under the grant along the following five lines:

a. Synthesis of suboptimal fixed-lag smoothers

b. A detailed survey of data smoothing

c. Stability of fixed-lag smoothers

d. Computational requirements in sequential smoothing

e. Nonlinear fixed-point smoothing

a. Synthesis

The mathematical synthesis of fixed-lag smoothers for continuous-time, stationary, random processes was developed by Wiener in the 1940's. However, practical synthesis utilizing lumped-parameter elements and networks is impossible since the smoother is infinite-dimensional. There is also a problem of internal stability. A useful approach to resolve these difficulties is that of approximate or suboptimal synthesis using

lumped-parameter elements. Two such synthesis procedures were developed and presented in [1] along with illustrative examples. The degree of suboptimality (in the sense of mean-square estimation error) can be made arbitrarily small by increasing the degree of the approximation, i.e., the number of elements. Both procedures yield design algorithms which are implementable on a digital computer. The second procedure, which is a generalization of the first, is quite flexible, but computationally more demanding. In particular, it specifies the synthesis problem as one of nonlinear programming.

b. Survey of data smoothing

This survey was undertaken to place in perspective the field of data smoothing relative to the broader area of estimation theory of which it is a part. The survey covers activity from the early work of Kepler and Gauss to that of the intensified research of numerous workers during the past ten to twelve years. Both theory and applications were examined, and directions for future research were indicated. A preliminary version of the survey was presented in [3]. The completed work which included over 115 references was published in Automatica [16].

c. Stability

An important fundamental question in connection with data smoothing algorithms is that of stability, particularly internal stability. Unless such algorithms are stable, their computational utility is, at best, extremely limited. A study of this question was reported in [9] for continuous-time, vector-valued, stationary, random processes for fixed-lag smoothing. A realization which is both bounded-input/bounded-output and internally stable was developed, and its use illustrated with an example.

d. Computational requirements

It is well known that while smoothing generally yields lower estimation

error variances than Kalman filtering, its storage requirements are more severe. To ascertain the extent of these requirements, a quantitative study of the issue was undertaken for all three forms of smoothing: fixed-interval, fixed-point, and fixed-lag. The results, which permit one to determine storage requirements exactly as a function of the dimension of the state vector and the length of the measurement data span are given in [12]. In addition, algorithmic procedures for minimizing storage requirements are included in the results.

e. Nonlinear fixed-point smoothing

Fixed-point smoothing has to do with estimating the state vector of a dynamic system at a single time point prior to that of the most recent measurement data. A representative problem here is that of determining the launch site coordinates of a missile from tracking data when the launch site is not visible to the tracker. A study of this class of problems for nonlinear dynamic systems, based on the marginal maximum likelihood estimation viewpoint, was presented in the doctoral dissertation of R. Eng (see Section V). A new, hybrid filtering-smoothing algorithm was derived and successfully applied to a problem of real-time aerial reconnaissance data processing for target location.

4. Applied Estimation Theory (Professor J. S. Meditch)

Two studies involving the estimation of respiratory system parameters from actual experimental data were conducted. The portion of the respiratory system involved was that relating tidal volume to alveolar CO_2. The results are of interest in the study of pilot stress in flight testing.

The first study [4] included the development of an adaptive step-size, random-search, optimization program to solve the associated nonlinear, least-squares estimation problem. The second, [8], was a survey

of the field of frequency response methods in the analysis of respiratory system regulation processes. It included application of the above computer program to estimate system parameters for humans.

5. Observer Theory (Professor J. S. Meditch)

Research in observer theory has been along three distinct lines. In the first of these, basic observer theory has been extended to permit state reconstruction for dynamic linear systems with unknown and unmeasurable inputs [17, 22, 23]. Potential applications include control systems where it is neither possible to model nor to measure disturbances which act on the system, e.g., spurious and unexpected wind gust loading on an aircraft, radiation from thermonuclear explosions, or communication system jamming and interference.

The second line of pursuit in the study of observer theory has been that of initial condition estimation and interpolation for linear systems. The problem of initial condition estimation, which has applications in post-flight data analysis and trajectory reconstruction, has been thoroughly studied in [19, 20, 33]. Both deterministic and stochastic process models have been employed, and the performance characteristics of all known algorithms for initial condition estimation have been analyzed. In the latter instance, specific recommendations for applications are included. As a follow-on to this work, observer theory has been extended to permit interpolation of data in state and parameter estimation. Two new types of observers, termed initial- and lagging-state observers, have been developed, and necessary and sufficient conditions for their stability derived [30, 43]. The first of these new observers permits exact reconstruction of the initial state of a linear dynamic system. The second provides sequential state reconstruction where the estimate is permitted to lag the most recent measurement time by a fixed amount. Both observer types are useful for exact state reconstruction during the

transient period of an identity observer where the latter is not able to estimate the state accurately.

In the third line of investigation into observer theory, direct links have been established between observer theory, optimization theory, and estimation for bandlimited, but otherwise arbitrary, signal processes [42]. Still a further connection has been made with the theory of system inverses [41]. Applications indicated in [41, 42] include image enhancement, digital picture processing in the presence of severe noise, and feedback control in the presence of intense, arbitrary disturbances.

6. Data Compression and Random Sampling (Professor A. R. Stubberud)

One advantage of the Kalman Filter is that the covariance equation can be pre-calculated, thus an error analysis of the filter is available before the filter is used. In many discrete time estimation problems, the arrival time of the observed data is random and even though the Kalman Filter theory is applicable, the *a priori* error analysis can no longer be obtained. Research was performed on the generation of bounds on the ensemble average of the covariance matrix when the data arrival times are random where the average is taken over the ensemble of all arrival times. This again allows *a priori* error analysis to be obtained.

A problem closely related to that of random arrival times is that of using data compression prior to filtering. In this problem, the data arrives at known times but as it arrives, it is tested and only if it meets certain criteria is it processed by the Kalman Filter. Thus from the standpoint of the filter the arrival times are random and furthermore they are dependent on the random properties of the input

data. Research was conducted to develop bounds on the average over the ensemble of arrival times of the covariance equation. These bounds are a valuable design tool to determine the value of data compression techniques in reducing the amount of filter processing which is necessary. Results of this study are presented in [45].

III. CONTROL THEORY

Research in control theory has focused largely on the development of tools for the design of multivariable control systems for both deterministic and stochastic processes. The results fall logically into the four areas described below.

1. <u>Computer-Aided Design</u> (Professor J. S. Meditch)

Two algorithms were developed and implemented on the XDS Sigma 7 to effect the computer-aided design of control systems. The algorithms are termed Generalized Polynomial Programming and Adaptive Random Search. The former is a new result, the latter an extension of a known technique. Both have been used to solve control system design problems for multi-input/multi-output plants which are subject to random disturbances. The overall synthesis procedure permits the inclusion of indirect saturation constraints, measures of closed-loop sensitivity, and limits on transient response.

Example problems which have been solved include:

a. Flight control system for a rigid body missile to minimize steady-state position error for a step input subject to a pole placement constraint in a region of the s-plane to guarantee that the damping ratio ζ and undamped natural frequency ω_n of the dominant mode satisfy certain inequality constraints. The latter then assures transient response quality.

b. Missile roll attitude control to minimize mean-square attitude error in the presence of wind gust disturbances subject to a mean-square constraint on control surface (aileron) deflection.

The results of this research are detailed in the doctoral dissertation of C. O. Jelinek (see Section V). A summary of the work appears in [13].

2. Design Theory (Professor J. S. Meditch)

It is well-known that both classical and modern control system design is considerably more difficult for multi-input/multi-output systems than it is for the single-input/single-output case. For example, the gain matrix necessary to achieve a specified closed-loop pole placement for single-input systems via state variable feedback is unique whereas its counterpart in the multi-input case is not. To overcome difficulties such as this and greatly simplify the associated computational problems, a technique for reducing the multivariable design problem to a single-input/single-output problem was developed and presented in [26]. The resulting designs are particularly attractive for problems involving regulation such as digital autopilots.

3. Controls-Configured Systems (Professor J. S. Meditch)

A complete theory of minimum-variance controls-configured systems has been developed along with a highly efficient computational procedure. The basic control problem addressed is that of specifying the feedback gain matrix for minimum-variance state regulation in the presence of white noise disturbances on the plant. The plant contains adjustable parameters which are subject to inequality constraints and nonlinearly related to each other. The latter constraints and nonlinear dependence are included in the problem formulation. Additional inequality constraints on the gain matrix elements are also present to prevent

excessively large gains in the closed-loop system. The problem was reformulated as one of nonlinear programming, and necessary and sufficient conditions for existence of a solution were derived. A computer program, built around the Generalized Reduced Gradient (GRG) algorithm of Abadie and Carpentier, was developed to implement the theoretical results. It has been applied to a lateral autopilot problem in which the plant (aircraft) has been partially reconfigured in specifying the controller. The results indicate a 20% improvement in disturbance rejection over previous designs. It has also been applied to a helicopter hover problem with the result of a 35% reduction in mean-square hover position error in the presence of random wind gusts relative to a "conventional" quadratic linear regulator design under the same conditions. The results of this study were presented in [37].

4. Multivariable Servomechanisms (Professor J. S. Meditch)

A theory of system type for describing the tracking properties of linear multivariable servomechanisms has been developed [38, 44]. New characterizations of system type have been formulated and two systematic methods for determining system type derived. Both methods are algorithmic and easier to apply than the techniques given in earlier studies. The first applies to the case where the open-loop system is described by its transfer function matrix, the second where its time domain state-space representation is given. New results have also been obtained for characterizing and identifying system type for certain composite systems from a knowledge of the individual subsystem types.

Methods for specifying pre- and post-compensation to achieve a desired system type in linear multivariable servomechanisms have also been developed [39]. Sufficient conditions have been derived for both forms of compensation when the compensator is restricted to a diagonal input-output representation, and a method for realizing reduced-order

pre-compensators has been presented for the case where the restriction is removed.

Certain of the above results have been applied to a previously proposed type r multivariable servomechanism structure to obtain a new configuration [34]. The latter possesses design freedom not present in the first configuration; this permits optimization of certain transient response properties of the closed-loop system without affecting previously specified system type and closed-loop pole location. An example has been given which demonstrates over a 35% improvement in integral-square tracking error relative to that for the original configuration.

The above work constitutes a complete and self-contained theory for the design of feedback control systems for multi-input/multi-output processes where one of the design goals is to achieve certain input-output tracking properties. The study involves the extension of the widely known and commonly used notion of system type from classical (single-input/single-output) control theory to multivariable systems as a convenient means for specifying control system tracking characteristics.

IV. PUBLICATIONS

Given below is a chronological listing of all publications that have resulted from the research conducted under this grant. It should be noted that References [10, 25, 27, 32] are the interim scientific reports that were submitted to AFOSR at the end of each of the first four years of the grant.

1. J. S. Meditch, "Synthesis of Sub-Optimal Fixed-Lag Smoothers," Proc. 9th Annual Allerton Conf. on Ckt. and System Th., Univ. of Ill., Urbana, Ill., pp. 24-31, Oct. 1971.

2. R. N. Crane and A. R. Stubberud, "Minimum Sensitive Linear Feedback Compensators," Proc. of the Fifth Asilomar Conference on Circuit and Systems, Nov. 1971, pp. 405-409.

3. J. S. Meditch and A. R. Stubberud, "A Survey of Linear and Nonlinear Smoothing," Proc. 1971 IEEE Conf. on Decision and Control, Miami Beach, Fla., pp. 160-161, Dec. 1971.

4. J. S. Meditch, P. J. Stoll and C. O. Jelinek, "Respiratory System Parameter Estimation Using a Random Search Method," Proc. 5th Hawaii Intl. Conf. on System Sci., Honolulu, Ha., pp. 247-249, Jan. 1972.

5. A. R. Stubberud and L. C. Westphal, "Mixed Strategy Solutions of Berkovitz's Differential Game Using the Method of Dual Cones," Proc. of the Fifth Hawaii International Conference on System Sciences, pp. 98-100, Jan. 1972.

6. R. W. Elsner and A. R. Stubberud, "A Model Approach to Fourier Transform Estimation," Proc. of the Fifth Hawaii International Conference on System Sciences, pp. 222-225, Jan. 1972.

7. R. F. Ohap and A. R. Stubberud, "Adaptive Minimum Variance Estimation in Discrete Linear Systems," Proc. of the Fifth Hawaii International Conference on System Sciences, pp. 306-308, Jan. 1972.

8. P. J. Stoll and J. S. Meditch, "Frequency Response Studies of Human and Avian Respiratory Regulation," Proc. 1972 Joint Automatic Control Conf., Stanford Univ., Stanford, Calif., pp. 108-111, Aug. 1972. (Invited paper.)

9. J. S. Meditch, "Stability in Fixed-Lag Smoothing," Proc. 1972 Joint Automatic Control Conf., Stanford Univ., Stanford, Calif., pp. 838-841, Aug. 1972.

10. A. R. Stubberud and J. S. Meditch, "Interim Scientific Report on Control Systems Theory," AFOSR Grant 71-2116A, School of Engr., Univ. of Calif., Irvine, Calif., Aug. 1972.

11. K. L. Hull and A. R. Stubberud, "Evaluation of the Performance of a Variance Estimation Algorithm Using Order Statistics," Proc. of the Third Symposium on Nonlinear Estimation Theory, San Diego, Calif., pp. 103-111, Sept. 1972

12. J. S. Meditch, "On the Data Storage Problem in Sequential Discrete-Time Smoothing," Proc. 10th Annual Allerton Conf. on Ckt. and System Th., Univ. of Ill., Urbana, Ill., pp. 68-75, Oct. 1972.

13. C. O. Jelinek and J. S. Meditch, "Control System Design Using Random Search and Geometric Programming Algorithms," Proc. 1972 IEEE Conf. on Decision and Control, New Orleans, La., pp. 168-169, Dec. 1972.

14. A. R. Stubberud and R. D. Sugar, "Computational Aspects of Multi-level Trajectory Optimization," Proc. 1972 IEEE Conf. on Decision and Control, New Orleans, La., pp. 309-314, Dec. 13-15, 1972.

15. A. R. Stubberud and R. N. Crane, "Closed Loop Formulations of Optimal Control Problems for Minimum Sensitivity," Chapter in Advances in Control Systems, vol. 9, ed. by C. T. Leondes, Academic Press, New York, 1973.

16. J. S. Meditch, "A Survey of Data Smoothing for Linear and Nonlinear Dynamic Systems," Automatica, vol. 19, no. 2, pp. 151-173, Mar. 1973.

17. G. H. Hostetter and J. S. Meditch, "Observing Systems with Unmeasurable Inputs," IEEE Trans. Autom. Contr., vol. AC-18, no. 3, pp. 307-308, June 1973.

18. A. R. Stubberud and W. K. Masenten, "Polynomial Estimators for Systems with Polynomial Nonlinearities," Proc. 1973 Joint Autom. Contr. Conf., Columbus, Ohio, pp. 224-231, June 1973.

19. G. H. Hostetter and J. S. Meditch, "Observers for the Computation of Initial Conditions," Proc. 4th Symp. on Nonlinear Estimation Th. and Its Appl., San Diego, Calif., pp. 132-134, Sept. 1973.

20. J. S. Meditch and G. H. Hostetter, "Estimation of Initial Conditions in Linear Systems," Proc. 11th Annual Allerton Conf. on Ckt. and System Th., Univ. of Ill., Urbana, Ill., pp. 226-235, Oct. 1973.

21. A. R. Stubberud and L. C. Westphal, "The Associated Maximization Problem for Separable Games," Mathematical Programming 5, pp. 374-380, 1973.

22. G. H. Hostetter and J. S. Meditch, "On the Generalization of Observers to Systems with Unmeasurable Inputs," Automatica, vol. 19, no. 6, pp. 721-724, Nov. 1973.

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24. A. R. Stubberud and R. G. Rains, "Optimal Sensor Configuration Control Applied to a Missile Launcher Problem," Proc. 1973 IEEE Conf. on Decision and Control, San Diego, Calif., pp. 739-741, Dec. 1973.

25. J. S. Meditch and A. R. Stubberud, "Interim Scientific Report on Control Systems Theory," AFOSR Grant 71-2116B, School of Engr., Univ. of Calif., Irvine, Calif., Feb. 1974.

26. G. H. Hostetter and J. S. Meditch, "The Reduction of Multivariable System Controller Design to a Single-Input/Single-Output Problem," Proc. 1974 Joint Automatic Control Conf., Univ. of Texas, Austin, Tex. pp. 303-308, June 1974.

27. J. S. Meditch and A. R. Stubberud, "Interim Scientific Report on Control Systems Theory," AFOSR Grant 71-2116C, School of Engr., Univ. of Calif., Irvine, Calif., Aug. 1974.

28. A. R. Stubberud and W. C. Martin, "Uncoupled Optimal Identification of Plant and Noise Parameters for Linear Dynamic Systems," Proc. of the 5th Symp. on Nonlinear Estimation and Its Appl., San Diego, Calif., Sept. 1974.

29. A. R. Stubberud and W. C. Martin, "An Additional Requirement for Innovations Testing in System Identification," IEEE Trans. Autom. Contr., vol. AC-19, no. 5, pp. 583-584, Oct. 1974.

30. J. S. Meditch, "On the Use of Observers for Interpolation," Proc. 1974 IEEE Conf. on Decision and Control, Phoenix, Ariz., pp. 866-871, Nov. 1974.

31. A. R. Stubberud and L. C. Westphal, "On the Computation of Solutions of Certain Dynamic Games," Intl. J. Contr., vol. 21, no. 2, pp. 193-202, 1975.

32. J. S. Meditch and A. R. Stubberud, "Interim Scientific Report on Control Systems Theory," AFOSR Grant 71-2116D, School of Engr., Univ. of Calif., Irvine, Calif., Aug. 1975.

33. J. S. Meditch and G. H. Hostetter, "Techniques for Initial Condition Estimation in Linear Systems," Intl. J. Control, vol. 22, no. 3, pp. 409-419, Sept. 1975.

34. C. A. Wolfe and J. S. Meditch, "A Modified Configuration for Linear Multivariable Servomechanisms," Proc. 13th Annual Allerton Conf. on Ckt. and System Th., Univ. of Ill., Urbana, Ill., pp. 801-808, Oct. 1975.

35. A. R. Stubberud and R. F. Ohap, "Adaptive Minimum Variance Estimation in Discrete-Time Linear Systems," Chapter 9 in Control and Dynamic Systems, Volume 12, ed. by C. T. Leondes, Academic Press, New York, 1976.

36. A. R. Stubberud and W. C. Martin, "The Innovations Process with Application to Identification," Chapter 4 in Control and Dynamic Systems: Advances in Theory and Applications," Volume 12, ed. by C. T. Leondes, Academic Press, New York, 1976.

37. R. F. Roberts and J. S. Meditch, "Optimal Regulation of Stochastic Linear Systems with Adjustable Parameters," Proc. 1975 IEEE Conf. on Decision and Control, Houston, Tex., pp. 476-481, Dec. 1975. Also, IEEE Trans. Autom. Contr., vol. AC-21, no. 1, pp. 100-104, Feb. 1976.

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39. C. A. Wolfe and J. S. Meditch, "Pre- and Post-Compensation to Achieve System Type in Linear Multivariable Servomechanisms," Proc. 1976 Joint Automatic Control Conf., Purdue Univ., West Lafayette, Ind., pp. 606-611, July 1976.

40. A. R. Stubberud and W. C. Martin, "An Uncoupling Method for Linear System Identification," IEEE Trans. on Autom. Contr., vol. AC-21, no. 4, pp. 506-509, Aug. 1976.

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42. G. H. Hostetter and J. S. Meditch, "Optimal Estimation Equations for Unknown Bandlimited Signals," Proc. 1976 IEEE Conf. on Decision and Control, Clearwater Beach, Fla., Dec. 1976. To appear.

43. J. S. Meditch, "Initial and Lagging State Observers," Info. Sciences, vol. 11, pp. 55-67, 1976.

44. C. A. Wolfe and J. S. Meditch, "Theory of System Type for Linear Multivariable Servomechanisms," IEEE Trans. Autom. Contr., vol. AC-22, no. 1, Feb. 1977.

45. H. Faridani and A. R. Stubberud, "Application of Data Compression in Optimal Sequential Estimators," submitted to IEEE Trans. on Autom. Contr.

V. PH.D. RESEARCH SUPPORT

Research leading to the following doctoral theses was supported in part or in full by AFOSR Grant 71-2116. All work was done at the University of California, Irvine.

1. K. L. Hull, "Sequential Estimation of Covariance Parameters of Discrete-Time Linear Dynamic Systems," June 1972. (Supervised by Professor A. R. Stubberud.)

2. R. G. Rains, "On the Choice of a System and Sensor Configuration for Optimal Linear Estimates," December 1972. (Supervised by Professor A. R. Stubberud.)

3. C. O. Jelinek, "Computer-Aided Design of Optimal Control Systems," March 1973. (Supervised by Professor J. S. Meditch.)

4. G. H. Hostetter, "Observers for Systems with Unknown, Unmeasurable Inputs," May 1973. (Supervised by Professor J. S. Meditch.)

5. R. Eng, "Fixed-Point Nonlinear Smoothing," June 1973. (Supervised by Professor J. S. Meditch.)

6. W. C. Martin, "The Innovations Sequence and System Identification," June 1974. (Supervised by Professor A. R. Stubberud.)

7. R. F. Roberts, "Minimum Variance Controls-Configured Systems," May 1975. (Supervised by Professor J. S. Meditch.)

8. C. A. Wolfe, "Linear Multivariable Servomechanisms," June 1975. (Supervised by Professor J. S. Meditch.)

9. J. W. Watts, "Initial State and Lagging State Observers," August 1975. (Supervised by Professor J. S. Meditch.)

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Polynomial filters	Data compression
Adaptive filters	Computer-aided design
Data smoothing	Controls-configured systems
Observers	Multivariable systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research conducted under AFOSR Grant 71-2116, Control Systems Theory, ~~during the five-year term of the grant, 1 July 1971 to 30 June 1976,~~ is comprehensively reviewed. The work is classified into two major categories of estimation theory and control theory. Within the former, results are reported in the areas of polynomial filtering, adaptive filtering, data smoothing, applied estimation theory, observer theory, and data compression and random sampling. In the latter, the focus is on multivariable control system design, and the (continued-over)

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20. Abstract (continued)

cont.

research presented is in the areas of computer-aided design, design theory, controls-configured systems, and multivariable servomechanisms. A chronological listing of 45 publications and 9 Ph.D. theses that resulted from the research supported by the grant is included.